Estimation of Ocean and Seabed Parameters and Processes Using Low Frequency Acoustic Signals

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LONG-TERM GOALS

The long term goals of our research are to:

- Understand, model and exploit the acoustic propagation physics in shallow water in the presence of ocean fronts and internal waves. This goal conforms to the major theme of the Shallow Water 06 experiment i.e. 3-D acoustic effects. The effects of oceanographic variability such as frontal meander, and internal solitary waves on 3-D acoustic reflection and refraction will be investigated.

- Improve inversion schemes for the estimation of sediment geoacoustic properties using low frequency broadband acoustic signals. The existing inversion method has been shown to successfully map compressional wave speed. The new work will focus on understanding the frequency and depth dependence of compressional wave attenuation and develop new inversion schemes for shear wave properties. We hypothesize that water-borne acoustic arrival properties such as their Airy Phase are sensitive to sediment shear properties. We hope to validate this hypothesis over the next period of investigation.

OBJECTIVES

We are proposing to address our goals with a series of objectives:

A. Characterize 3-D acoustic variability due to internal waves and fronts.

The tasks associated with this objective are:

1. **Data analysis:** Acoustic signals transmitted from the R/V Sharp in the Shallow Water 06 Experiment at various ranges and angles to the WHOI Shark Array and Single Hydrophone Receive Units (SHRU) are being analyzed.
2. **Calculate various intensity metrics:** Different intensity metrics will be calculated, including scintillation Index (SI), integrated energy over the depth of the array and over the duration of the acoustic signal, temporally integrated energy over the duration of the acoustic signal on a single hydrophone, single hydrophone intensity observations.

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3. **Modeling:** A number of representative events will be modeled with and without the sound-speed profile of the measured internal wave in order to explore and compare the effects of the internal wave on acoustic propagation and intensity variability with measurements.

PhD student Georges Dossot carried out on this study as part of his dissertation topic. We worked in close collaboration with Dr. Mohsen Badiey (University of Delaware), Kevin Smith (Naval Postgraduate School), Dr. James F. Lynch and Dr. Y.-T. Lin (Woods Hole Oceanographic Institution).

B. Long Range Sediment Tomography using Combustive Sound Sources (CSS)

The tasks associated with the long range sediment tomography objective are:

1. **Investigate the effect of shear on compressional wave dispersion**: Effect of shear on the modal dispersion was investigated. Estimates of shear wave velocity can be made based on this analysis.
2. **Develop new inversion techniques for shear properties**: A new inversion scheme is being developed to estimate shear properties of the sediment using interface wave dispersion. The instrumentation and other assets (including horizontal bottom-mounted geophone array) required for this task were recently acquired under the DURIP program. We are working closely with Preston Wilson (ARL, University of Texas) in this topic.
3. **Finite Element Modeling of wave propagation**: Doctoral student, Hui-Kwan Kim, is modeling wave propagation within short ranges. He is investigating the possibility of using commercial software Abaqus to model interface waves.

APPROACH

The PIs (James Miller and Gopu Potty) took part in the SW-06 on the R/V Knorr and participated in the CSS deployments. Effect of shear on modal dispersion was studied using the Shelfbreak Primer data collected in 1996. Then graduate student George Dossot also participated in the experiments in the R/V Sharp. Transmissions from the R/V Sharp were used to investigate for the evidence of intensity fluctuations associated with internal wave interaction with acoustics. Modeling using a 3-D propagation code (3D PE) is being done to confirm these intensity fluctuations. A shear measurement system consisting of geophone/hydrophone array and WHOI-SHRU data acquisition system was designed and developed as part of a DURIP grant. Data were collected during two field tests which will be used to develop a scheme to estimate shear properties.

WORK COMPLETED

The data from SW-06 is being analyzed and preliminary results have already been presented at ASA meetings. A JASA- EL article has been published based on our inversions using Combustive Sound Sources (CSS). Graduate student George Dossot has been working on the data from R/V Sharp transmissions received on the WHOI- Shark VLA. He has completed the analysis of the data and modeling the propagation to include the effect of internal waves using a 3D Parabolic Equation code and 3D Kraken. George Dossot has completed his Ph. D dissertation and is currently preparing manuscripts based on this work for publication. Another graduate student, Jeannette Greene, designed and performed limited testing of a shear measurement system as part of her Master's thesis work.

Another full-scale sea test was conducted in collaboration with ARL, UT (Preston Wilson, PI) in August, 2011 in Narragansett Bay and off Block Island. PhD student Hui-Kwan Kim is focusing on finite element modeling of wave propagation.

RESULTS

1. Acoustic variability in the presence of internal waves

Georges Dossot, as part of his doctoral dissertation research, examined the extreme variations of acoustic signals in the presence of internal waves. Specifically, we focused upon the intensity fluctuations of acoustic transmissions made by the R/V Sharp during the Shallow Water 2006 (SW06) experiment. Internal waves are known to cause extreme fades and intensifications of acoustic signals that pass through (or near) them depending on the angle between the propagating internal wave and the source-receiver pair. We are most interested in acoustic signals that pass parallel (or nearly parallel) to the internal wave front because this configuration leads to a “ramping” of acoustic intensity which anticipates the arrival of the internal wave.

The R/V Sharp experienced over fifty internal wave events while participating in the SW06 experiment. Throughout the experiment, the R/V Sharp transmitted broadband acoustic signals using a J15 acoustic source at various angles in relation to the WHOI receiving arrays. This experimental configuration was purposefully done in order to examine the angle relationship between the source-receiver path and propagating internal waves. Environmental sensors aboard the R/V Sharp and on the deployed moorings were investigated for each event to determine the size and structure of the internal wave. These events were catalogued in a web-based archive and organized in a manner which prioritized promising datasets for acoustic analysis.

Data analysis prior to FY11 showed that several of the R/V Sharp’s datasets yielded significant ramping of acoustic signals in anticipation of an approaching internal wave, and additional fluctuations as the wave packet passed. The ramping phenomenon can be attributed to a three-dimensional version of the Lloyd’s Mirror effect; which causes acoustic signals to refract off the approaching internal wave front, resulting in multiple arrivals (and signal intensification) at the receiver. The fluctuations due to the passing wave packet can be attributed to a combined interference pattern due to two primary causes. Firstly, as an internal wave soliton passes over the source-receiver path, a large shadow zone can occur, spreading the energy outwards. Secondly, as a wave packet passes, “ducting” can occur which traps the signal between solitons, and yields extreme signal intensification.

Our efforts over the past year have focused on modeling the sound field to better understand the phenomena we believe to be taking place. We have worked closely with the Naval Postgraduate School to enhance (and make use of) the three-dimensional Miami-Monterey Parabolic Equation (MMPE) code. By implementing a customized three-dimensional sound-speed profile, we have accurately modeled the trends apparent in Event 44. Repeated model runs have simulated the time dependence of the approaching internal wave and replicated the intensity fluctuations that we have seen in the measured data.

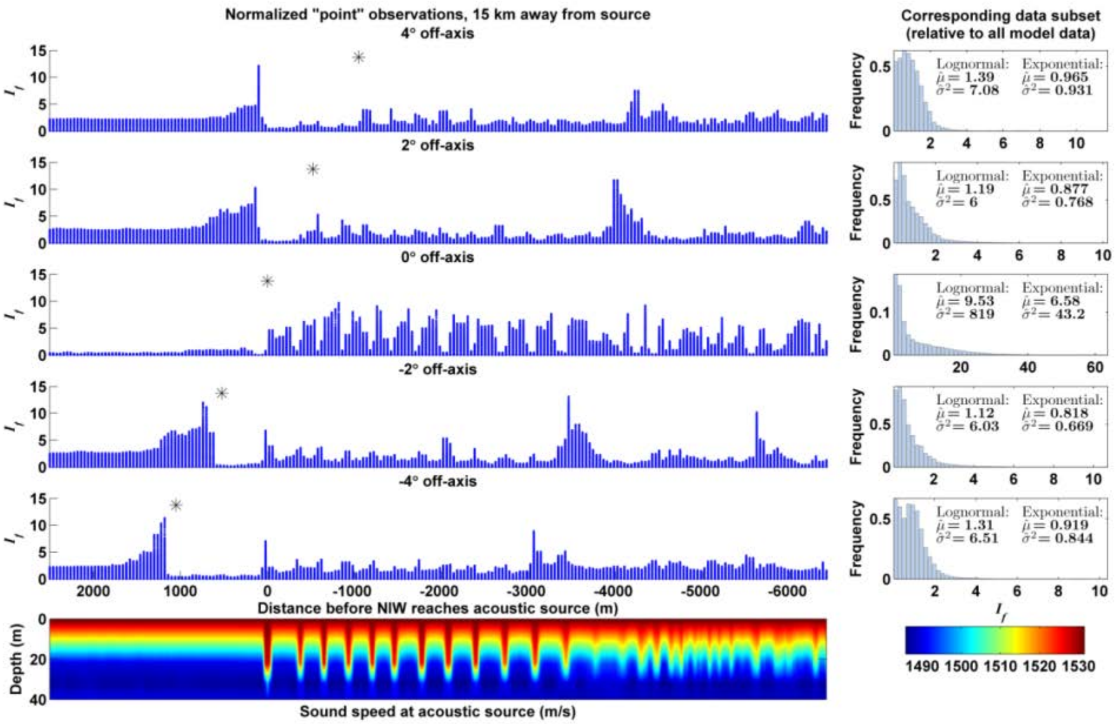

Figure 1: Energy dependence for instances where the acoustic track is nearly parallel to the NIW front. Acoustic angle is varied between ± 4˚ to show large variability of acoustic receptions for very small angle variations. Left-most panels simulate the NIW marching across distance (or time). These data re normalized for each individual plot. Right-most panels show the associated distributions with the expected mean and variance annotated. Mean and variance values are referenced to the entire model data set. NIW sound speed at source provided as a reference. First soliton arrival at each receiving location is marked by the asterisks.

We are most interested in the impact of small angle differences between the source-receiver path and the propagating internal wave train (between ± 4˚). To simulate the propagating NIW field over space and time, we employed a bank of thirty computers over a one-week period. This corresponded to roughly 4,000 individual three-dimensional MMPE runs, which sampled the acoustic signal at seventeen frequencies over the 100-300 Hz bandwidth, and propagated the NIW ten kilometers in forty-meter marching increments. To put this in context, it is similar to modeling a water mass (with constant eighty-meter depth) the size of the Red Sea! Figure 1 shows expected energy arrivals upon each array based upon repeated PE simulations. The five top-left panels show point measurements which simulate energy receptions over time, each plot representing an individual array at 4˚, 2 ˚, 0 ˚, -2 ˚, and -4 ˚ off-axis. These data are re-normalized such that the mean energy in each panel is unity; this is done so that we can more easily interpret results across a constant scale. In order to directly compare energy fluctuations at different angles, one can refer to the histograms shown on the right, where the histogram data were not re-normalized, and are a direct subset of the entire aggregate model dataset. As a reference, the NIW sound speed profile is plotted below, and represents what the acoustic source is experiencing versus time. This profile is also valid for the absolutely parallel case since it extends uniformly across range. However, it is not representative of what the other receiving

VLAs experience, since they will observe a "shifted" version of the same profile. An asterisk is placed at the point where the first soliton reaches the VLA to help interpret this relative shift. The conclusion to be made from this effort is that relatively small azimuthal changes between the source-receiver path and the approaching internal wave can cause dramatic differences in the character of received acoustic fluctuations.

2. **Effect of shear on the modal dispersion:**

There has been renewed interest in understanding the effect of shear on compressional wave propagation, especially attenuation. The role of shear conversion in modifying the frequency dependence of attenuation has been the subject of some recent publications. We have tried to investigate the effect of shear on the modal propagation and attenuation. We used a simple elastic half space sediment model and followed the approach introduced by Tolstoy[1] to calculate the theoretical model dispersion. We iteratively adjusted the shear speed and eventually matched the observed dispersion reasonably well as shown in Figure 2 (data from Primer experiment).

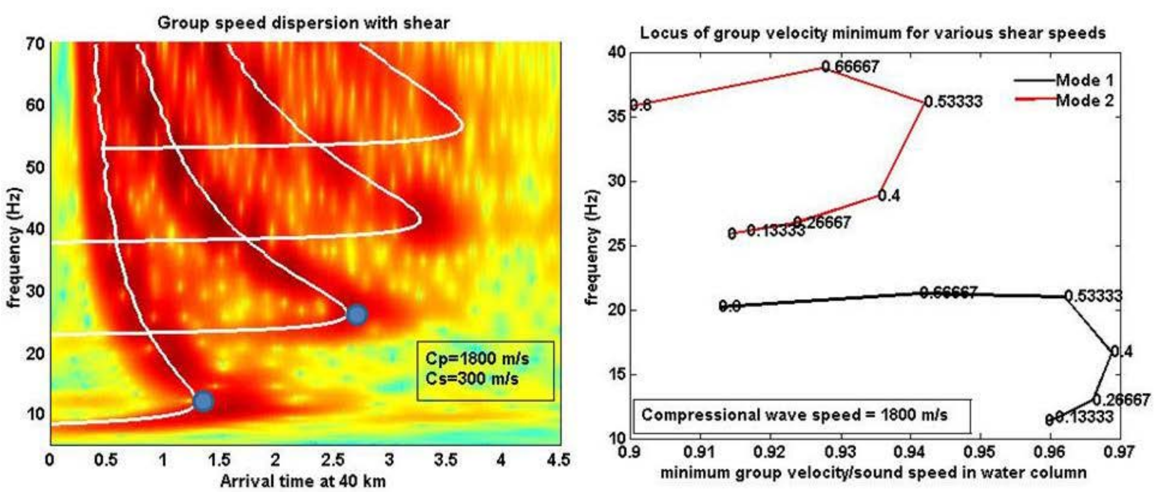

Figure 2: Left panel shows the calculated and observed modal arrival times. The continuous white lines are the modal arrival times calculated for a half space elastic sediment model with a compressional speed of 1800 m/s and a shear speed of 300 m/s. The right panel shows the locus of group velocity minimum for various shear speeds. The numbers indicate shear speed divided by water column sound speed.

Left panel in Figure 2 shows the calculated and observed modal arrival times. The continuous white lines are the modal arrival times calculated for a half space elastic sediment model with a compressional speed of 1800 m/s and a shear speed of 300 m/s. The right panel shows the locus of group velocity minimum for various shear speeds. The numbers indicate shear speed divided by water column sound speed. The difference in group speed minimum, for a shear speed of 300 m/s, between mode 1 and mode 2 is 65 m/s from the right panel. This translates correctly into the arrival time difference between mode 1 and mode 2 minimums (shown as blue circles) as shown in the left panel. The frequencies correspond to the mode 1 and mode 2 group speed minimum are 12.5 Hz and 26.5 Hz respectively which match well with data.

3. Shear Measurement System based on interface wave dispersion:

We have acquired a geophone/hydrophone array under a DURIP grant (*Seafloor Shear Measurement Using Interface Waves*, Miller and Potty PIs) capable of collecting interface wave data. Using the dispersion characteristics of the interface wave data we plan to invert for shear wave speed. One of our graduate students, Jeannette Greene designed and performed limited testing of this system as part of her Master's thesis work.

This limited seabed test, using some of the components of the shear measurement system, was conducted north of the R/V Endeavor Pier in the Narragansett Bay Campus of the University of Rhode Island on March, 2011. One SHRU and a four geophone array were deployed off the stern of R/V Endeavor in approximately 6 m of water. The geophones were properly placed, with a spacing of 5 m underwater, with the help of divers. The layout is shown in Figure 3. A 300 lbs weight was released from just below the surface of the water off the stern of R/V Endeavor using the ship's capstan. Data were collected by repeating the weight drops ten times.

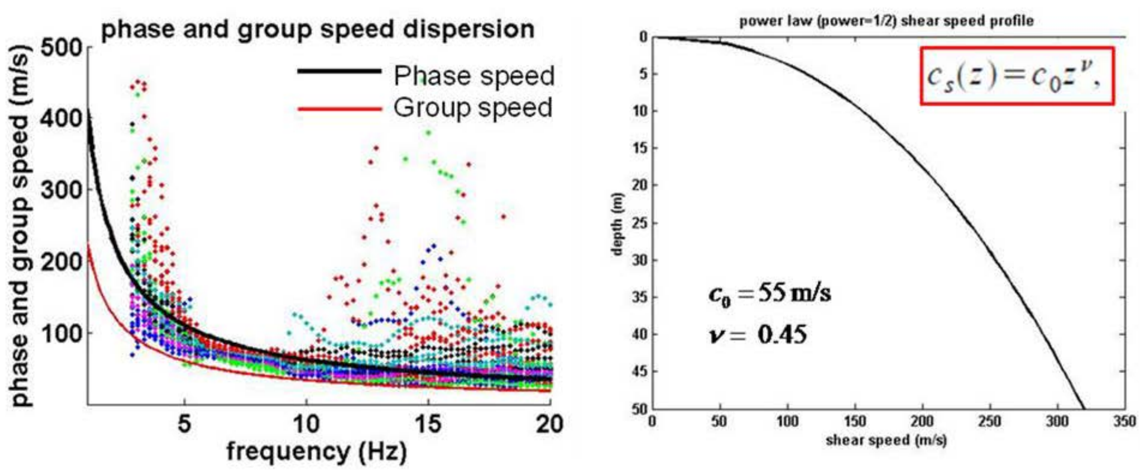

Figure 3: Phase velocity estimates (in color dots) from all possible geophone-event pairs (left panel). The continuous lines are theoretical group and phase velocity curves calculated using the Chapman-Godin approach for mode 1.The right panel shows shear wave speed profile used to calculate the theoretical group and phase speed curves shown in the left panel.

The signals received on the four geophones were used to calculate the phase velocity as a function of frequency. Cross spectral density between signals from a geophone pair provides an estimate of the phase difference between them. Phase velocity is calculated knowing the phase difference. The phase speeds calculated using all the possible event-geophone pairs are shown in Figure 3 (left panel). The phase velocity estimates from different event-geophone pairs are shown in different colors in this figure. As can be seen from the figure, the phase velocity estimates tend to become noisy at frequencies close to above 20 Hz. The phase and group speeds calculated theoretically based on Chapman- Godin approach[2] is overlaid on the data in the figure. The theoretical curves shown in the figure correspond to mode 1. A time-frequency analysis of the time series data also confirmed the presence of mode 1 at this frequency band. It should be noted that the phase speed estimation assumes

range independent sediment properties which is a reasonable assumption given that the ranges involved are very small in the present test. The theoretical phase and group velocity curves shown in the left panel of Figure 3 have been calculated based on a shear wave speed profile shown in the right panel. The shear wave speed profile ($c_s(z)$)shown in the right panel is a power law approximation ($c_s(z) = c_0 z^{\nu}$) with c_0= 55 m/s and ν=0.45. The values of $c_0$and ν were arrived at iteratively by choosing trial values for c_0 and ν, so that the phase speed dispersion matches the Scholte wave dispersion data as shown in the left panel.

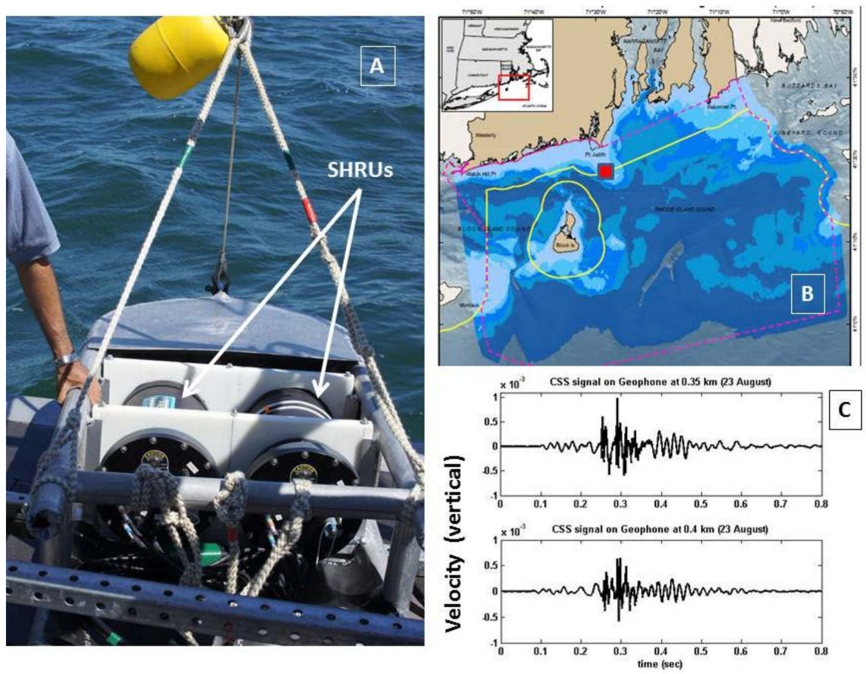

Figure 4. The sled which houses the SHRUs is ready to be deployed (panel A). The geophone array will follow the sled into the water. One of the locations were the geophone array was deployed during the August, 2011 sea test (panel B). Panel C shows the first look at the data on a geophone from two shots at 0.35 km (upper panel) and 0.4 km (lower panel) . Y-axis indicates the amplitudes of the vertical velocity and x-axis is arbitrary time.

Another full-scale sea test was conducted during 22-25, August 2011 in Narragansett Bay and off Block Island, RI. One of the locations of testing, north-east of Block Island in 40 ft of water depth, is shown in panel B of Figure 4. We accomplished three days of testing of the geophone array and the Combustive Sound Source (Preston Wilson, ARL, UT Texas) which were deployed by R/V Shanna Rose. Two SHRUs were housed in a sled and the geophone/hydrophone array was laid out behind the sled. Panel A in Figure 4 shows the sled with the SHRUs is ready for deployment. The geophone array was deployed after the sled and the sled was dragged for a short distance to straighten out the array. The data is being process now and initial look at the data indicates that the test was a successful one. The time-series recorded in one of the four geophones due to a CSS shot is shown in panel C of Figure 4. Y-axis indicates the amplitudes of the vertical velocity and x-axis is arbitrary time.

We plan to complete the processing of the data from the test and try to invert for the shear properties of the bottom using the method adopted in our earlier test. We have some ground- truth measurements available in some of the test locations in the form of geotechnical information. These were collected as part of the Rhode Island Offshore Wind Farm study. We plan to use this data to compare and validate our shear speed estimate.

IMPACT/APPLICATIONS

The inversion scheme using explosive sources is suitable for rapid estimation of acoustic properties of sediments in shallow water. This method is cost effective as a single sonobuoy and air-deployed explosives can provide the data. Using multiple sources and receivers sediment properties would allow an area to be mapped. 3-D propagation effects are important to naval applications as it can cause fluctuation in the acoustic field of the order of 5 to 10 dB. The understanding of the causes of these large fluctuations in transmission loss will aid their possible exploitation in ASW.

TRANSITIONS

The sediment parameters obtained by this inversion will compliment the forward modeling efforts. The sediment tomography technique is suitable for forward force deployment when rapid assessment of environmental characteristics is necessary. In addition to naval air ASW applications using sonobuoys and SUS charges, this technique would be compatible with Navy special operations involving autonomous vehicles.

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HONORS/AWARDS/PRIZES

James Miller and Gopu Potty participated in the Second INDO – US Workshop on Shallow Water Acoustics, National Institute of Ocean Technology (NIOT), Chennai, India, February 9-11, 2011.

Gopu Potty offered a week long course on *Ocean Acoustics* for emerging researchers and scientists in India at National Institute of Ocean Technology (NIOT), Chennai, India, February 2-8, 2011. This course was sponsored by ONR and NIOT, India.

Gopu Potty was appointed as Associated Editor for IEEE Journal of Oceanic Engineering starting July, 2011.

James Miller and Gopu Potty were approved as co-chairs of the Acoustical Society of America Providence, RI meeting to be held in 2014.

Gopu Potty was nominated to the Advisory Committee and Technical Program Committee of the International Symposium on Ocean Electronics organized by the Cochin University of Science and Technology in Cochin, India (November, 2011).

James Miller has been nominated for President of the Acoustical Society of America and the election is scheduled for 2012.